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**A NEW SHIPBUILDING MEASUREMENT TOOL
PHOTOGRAMMETRY FOR MEASURING
CIRCULARITY OF SUBMARINE HULLS**

BY

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ABSTRACT

Photogrammetry is the art, science, and technology used in the interpretation of coordinate data about physical objects by the measurement and analysis of photographic images. The Electric Boat Division of General Dynamics utilizes photogrammetry primarily, in measuring the as-built circularity (out-of-roundness) of the TRIDENT Class pressure hull cylinders. Various other mechanical methods had been used in the past for measuring hull circularities; but the unique features and capabilities of photogrammetry proved itself well to meet demanding shipyard needs. The large awkward shape of submarine pressure hull cylinders, in combination with the flexibility and ease of the photogrammetric technique, makes photogrammetry a productive tool for Electric Boat's shipbuilding applications.

INTRODUCTION

Electric Boat Division first employed the *use of* photogrammetry for the purpose of measuring the circularity of the SSBN726 TRIDENT Missile Compartment. The major problem in measurement of this compartment were the circularity measurements to be taken in the area of the missile tubes (large masses of welded in structure) which protrude from the hull. This condition made it very difficult for conventional methods to be implemented. In current submarine construction, it is required that circularity measurements be taken at frame and mid-bay locations at regular intervals along the length of the pressure hull. Photogrammetry provided an accurate means that could be used in way of this missile tube structure.

The United States Navy, Electric Boat's primary Customer, requires by specification that all TRIDENT sub marines meet a Navy specified tolerance for any point deviating from a measured circle encompassing the circumference of -the pressure hull cylinder. Navy specifications also detail *a variety of* mechanical methods that can be used in taking hull circularities. (1) These methods include: the bridge gauge method, internal swing arm internal radii, method of optical squares, and the external template method. The internal radii method is employed at our Hull Cylinder Manufacturing Facility at Quonset Point, Rhode Island. Internal Circularities can be taken at internal measurement stations within a hull cylinder, this must be performed after all major welding has been accomplished in this area. This method of taking circularities has proven reliable and accounts for approximately 37% of the total measured hull circularities taken on a TRIDENT submarine. External hull circularities again have to be taken after major welded in structure has been installed such as the missile tubes, decks, foundations, tanks and after cylinder hull butts

have been welded. Thus, external circularities are primarily taken at Electric Boat's Groton, CT facility where final fit-up and assembly of the TRIDENT pressure hull cylinders takes place. Electric Boat, in the past, had used an external wooden template in taking these external circularities. The method of taking external hull circularities by means of an external template lends itself well when taking circularities over a round cylinder less than 30 feet in diameter, but the condition of taking a hull circularity in way of a protruding missile tube all but eliminated the use of the external template method from consideration. Recently, the use of the external wooden template has been replaced by photogrammetry in taking all external circularity measurements on the TRIDENT pressure hull cylinders.

PHOTOGRAMMETRIC MEASUREMENT

A brief on this measurement "tool" follows and it is presented as a consolidation of descriptive information extracted from several sources in the photogrammetry profession.

"Broadly described,. photogrammetry is an indirect measurement process. It is the process of extracting meaningful two or three dimensional measurements of a scene from one or more photographs of the scene. The derived information may be in the form of coordinates of points, distances, outlines of features or shapes of surfaces. Following a photographic phase, which is usually performed on the Customer's site, the exposed film which is in the form of highly ground flat glass plates are brought back to the vendors office for analysis. Measurement of discrete points on the image are made directly off the negative plate by the use of analytical comparator. The comparator digitizes each point on the image to a X, Y photogrammetric coordinate grid system

Subsequent numerical triangulation produces a digital model of the scene which in turn is processed to yield numerical and/or graphical results. The numerical information so derived may be in the form of coordinates of points, distances, outlines of features or shapes of surfaces. Measurement accuracies are well established, for example, the method using fully analytical photogrammetry yields tolerances upwards of ± 1 part in 60,000 of the major dimension of the scene photographed.

The desired dimensional data of the scene photographed can be obtained through several combinations of photogrammetric processes. The various possibilities are diagrammed in Figure 1. For most shipbuilding measurement applications, fully analytical photogrammetry is preferred, since it offers point data of higher accuracy than either the analog or semi-analytical methods.

The unique capability of photogrammetry is considered a complement to, not a substitute for, conventional measurement methods.

Some advantages of measuring with photogrammetry are when:

- 1) Complexity of shape or detail of the scene is restrictive.
- 2) Relative directions to all points of interest within the field of view of a camera are recorded instantaneously.
- 3) All data can be obtained in a short period, minimizing the effect of thermal and gravity induced changes.

- 4) Due to the short period of time to take photographs, there is a minimum interference with ongoing work. In some instances, work can proceed without interruption.
- 5) Orientation of attitude of the scene is of no consequence as long as there is room to stand off with the camera.
- 6) Photographs may be taken and achieved for any potential need to produce data at a future point in time.

There are some disadvantages to the photogrammetric measurement method, notable;

- 1) Results of photogrammetric measurements are not produced instantaneously.
- 2) Useful photographs cannot be taken in heavy rain, snow, or fog.
- 3) Measurements in very confined spaces are generally not practical due to the large number of photographs which must be used to cover the entire scene. " ---

IMPLEMENTATION OF THE METHOD AT ELECTRIC BOAT DIVISION

The potential of photogrammetry for submarine hull circularity measurement was apparent after assessment of the work of investigators who prepared the report "Photogrammetry in Shipbuilding" under MARAD sponsorship(2). As early as March, 1977, this method's apparent usefulness for hull contour measurement was identified in an in-house new construction technology brief.

Conversations were then initiated with a vendor of photogrammetric services, J. F. Kenefeick, to investigate measurement of a hypothetical, long, large diameter cylinder, accessibly only from the outside. After developing tentative photographic scheme, Kenefick performed a computer simulation of the problem and determined that photogrammetry was a viable solution to the measurement task and that data could be produced within the tolerance of $f \pm 0.05$ inch.

We have noted that photogrammetry was not an approved method for circularity measurement, however, receptivity of this new method by SUPSHIP, Groton, NAVSEA PMS396, and Shipyard Operations allowed planning and subsequent implementation to proceed with their full cooperation. (3)

PHOTOGRAMMETRIC MEASUREMENT OF MISSILE COMPARTMENT HULL CIRCULARITY - SSEN726

The shipyard site and the "object" to be measured is best described by referring to Figures 2 through 5. Figure 2 is an overview of the TRIDENT Missile Compartment within the assembly building. Figure 3 shows the typical ship support system (strongback and poppets) and is an obstacle to line of sight to some points of interest. Figure 4 shows missile tube projections which make the simple cylinder an irregular object. Figure 5 is representative of points of interest (target and station layout) on the hull cylinder.

Planning

A photogrammetric plan for the TRIDENT hull survey was developed which considered placement of the photogrammatist and the camera's available working space, field of view of the camera, depth of focus and the level of accuracy desired.

Two data processing phases are employed: 1) photogrammetric triangulation to obtain the dimensional coordinates for all the targets, and 2) manipulation of these coordinates to translate and rotate coordinates into a meaningful system and calculation of a circle best fitting a series of points.

The target coordinate measurements are processed through vendor-developed software computer package3 to accomplish the mathematical solution of an analytic multiray photogrammetric triangulation.

Data manipulation consists of calculation of the plane which best fits all targets on the measurement station and calculation of the circle in that plane which best fits the same targets.

The quality of the solution is assessed by checks of measurement residuals, standard deviations of target coordinates, and fit to scale reference distances.

Results from data processing are tabular listings of point departures from the least squares solution mean radius at the 10° increments, this is shown graphically for a frame in Figure 12.

The point departures and mean radius input directly to the Electric Boat Division computer program which iterates the data and assesses whether the maximum acceptable deviation has been exceeded. Figure 13 is typical of the output form which Electric Boat uses to document each measured circularity station.

1. target's image must be on two or more photographs in order for it to be triangulated.

2. F. Kenefick currently uses the WLD AC-1 Analytical Comparator. Direct reading to .001mm with the two Axis Digitizer can be achieved. Figure 11.

3. "Close range analytical bundle solution".

SOME GENERAL COMMENTS RELATIVE TO THE METHOD USED

- 1) The initial photography effort required seventy-seven(77) photos on the SSBN726, forty-four (44) of which were for the forward-most fifteen (15) measurement stations. These were taken on a Saturday, the balance, thirty-three (33) were of the after ten (10) stations and were taken on Sunday. The entire photographic process; including shipyard supporting activities, was completed in a weekend.
- 2) Experience gained on SSBN726 and subsequently on SSBN727 enabled the photogrammist to revise the SSBN728 photo plan to fourteen (14) photo frames per station, thereby increasing the total photos to ninety-eight (98). In addition, the 5° targets were deleted to remove the bias resulting from an excess target population on the ships sides, which was in evidence in the SSBN726 survey results.

- 3) On SSBN728, less time was taken to perform the photography allowing time for overall "tie-in" photos of the missile compartment to be taken. It is now possible to relate station circles and the point departures therefrom to the ship's coordinates. In turn, this enables photogrammetric triangulation of all data points on the hull. These results can, at some future date, provide offsets from which to construct an as-built body plan of the missile compartment section of the hull.
- 4) Measurement of the negatives and data processing performed on a routine basis has taken an average of twelve (12) weeks, thus it is evident that results of photogrammetric measurements are not produced instantaneously.

OTHER USES

- 1) Electric Boat Division has utilized photogrammetry in recent months in some different applications. One application is the measurement of the flatness of the interfacing surface between the Bow Dome to the non-pressure hull frame, see Figure 14. Construction tolerances require a specified flatness be maintained over the depth and circumference of this interface. Due to a variety of hull considerations, particular attention has been given to this problem in determining and maintaining the flatness over the area.

In the construction of the early SSBN's Electric Boat Division hired an outside subcontractor to machine this interface to meet the proper flatness requirements. In the construction of the more recent SSBN's, Electric Boat Division has assumed the role of trying to maintain this

flatness requirement, but with limited success.

Electric Boat Division made the decision to bring in an outside vendor to determine the flatness at this frame surface.

GEOD Corp. of Oak Ridge, New Jersey was given the task of providing raw coordinate data about this frame interface by the use of photogrammetry. Measurement stations were layed out at 180 locations around the circumference at every 2°. In addition, at each circumference station, targets were marked at 4 equally spaced locations along the depth of the frame, totaling 720 locations to be measured. GEOD used the technique of comparing overlapping photos in a stereo pair solution. In this way, the flatness of the frame interface could be better determined.

The end product of this effort, was the determination of the maximum high and low point deviations measured through a best fit plane of the frame interface. with the raw coordinate data received from the vendor, engineering personnel inputted this data into Electric Boat Division's CAD system so as to develop a contour map detailing the high and low points of the frame interface, Figure 15. The shipyard then utilized this information to determine what areas of the frame interface they should-machine to bring the frame within drawing tolerance.

- 2) Electric Boat has used photogrammetry to measure the hull contours of one of the 688 Class Submarines. The purpose was to develop the profile of the exterior surface of the hull, so a precise mounting of special hull equipment could be accomplished. The tolerances for installation of this equipment are required to be very exact.

Photogrammetry was one of the few methods known that could provide this type of information with the accuracy required and within the time allotted during the ship availability.

3) In addition to the uses described earlier, potential applications for photogrammetric measurement under evaluation at Electric Boat Division. These include:

- Hull plate mapping for backfit installations**
- Pipe targeting - as a replacement for wire templates**
- Sphericity of hemihead end closures**
- Graving dock cell movements with time or events**
- Propeller/blade measurement - to obtain accurate as-built dimensions for comparison of one propeller to another**

4) Other shipyards have employed this new shipyard tool for measurement of large irregular shaped ship elements. As an indication of the expanding use in shipbuilding activities, briefs of some specific recent photogrammetric surveys and their attained tolerances are reported as follows:

- o A three dimensional survey of the bottom section of the 1,035 feet tall COGNAC drilling platform jacket structure. The section is 175 feet high and measures 342' x 325' at the bottom and 311' x 283' at the top. Locations and elevations were determined to 0.12 inch tolerance - Shell Oil Co. (4)**
- o Determine three dimensional geometry of a 24 ton FFG strut casting as a QC measure. Tolerance achieved $\pm .03$ inch - Todd Pacific Shipbuilding.**

- o Check the alignment of the center of the "Palar Star" rudder palm and the *axis* of the gudgeon and parallelism between palm and counterbore of the gudgeon. Tolerance achieved $\pm .02$ inch over all surfaces of the 15' x 17' rudder - U. S. Coast Guard.
- o Produce three dimensional coordinates of approximately 450 points distributed over the surface of a DD963 Sonar Dome Rubber Window (Lg 38', Breadth 20, H₅ 8'). Tolerance of coordinates was ± 0.03 inch - Ingalls Shipbuilding.
- o Surveying mating surfaces of as-built halves of a 126,000 DWT Tanker.(5)
- o Checking as-built dimensions of body. plans for new Navy Class Frigates.

IMPLEMENTING IN-HOUSE CAPABILITY

Electric Boat Division has considered the option to acquire in-house capabilities to perform its own photogrammetric measurements in the shipyard. Several aircraft companies and at least one other shipyard have acquired this capability. Photogrammetry should only be established in-house when the number occasions, wherein this special measurement method technically warrants the capital investment and training entailed. One could project that a team with in-house capability at one Corporate Division having the primary work load, could serve other Divisions on a call basis and offer contact services on a not-to-interfere basis.

In adopting photogrammetry as a measurement tool the Shipbuilder can select from three alternatives.

- o Develop total in-house capability**
- o Retain a photogrammetrist by subcontract**
- o Use an in-house/subcontract combination**

A photogrammetric unit to be totally self sufficient requires hardware, software and training of the team

Initially, a dedicated two man team, a person experienced in photogrammetry and a shipyard technical person, would be required. If in-house computer support is available, approximately a three month start-up period should be allowed.

CONCLUSIONS

Photogrammetry is a relatively new, proven, measurement tool for shipyards. Although it is not a real time measurement system, it does offer minimum disruption to production, immediate implementation, and greater accuracy than other methods for measurement of objects of irregular shape complicated by size or object accessibility.

Whether the modest investment to obtain in-house capability, or contracting for services, best suits a shipyard depends simply on the number of special measurement surveys found necessary in the performance of work under contract.

The method complements the shipyard measurement tool inventory, it does not displace other conventional and convenient measurement tools.

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National Shipbuilding Research Program
U. S. Department of Commerce,
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- (3) **Circularity Measurements of Submarine Hulls by**
Photogrammetry - Final Report - November 1978
- (4) **Photogrammetric Surveys of Cognac - J. F. Kenefick**
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- (5) **Predicting the Fit of Ship Built in Halves -**
J. F. Kenefick and D. D. Peel,
1978 International Society of Photogrammetry
Symposium - Stockholm Sweden
Prepared for General dynamics/Electric Boat
Division by J. F. Kenefick

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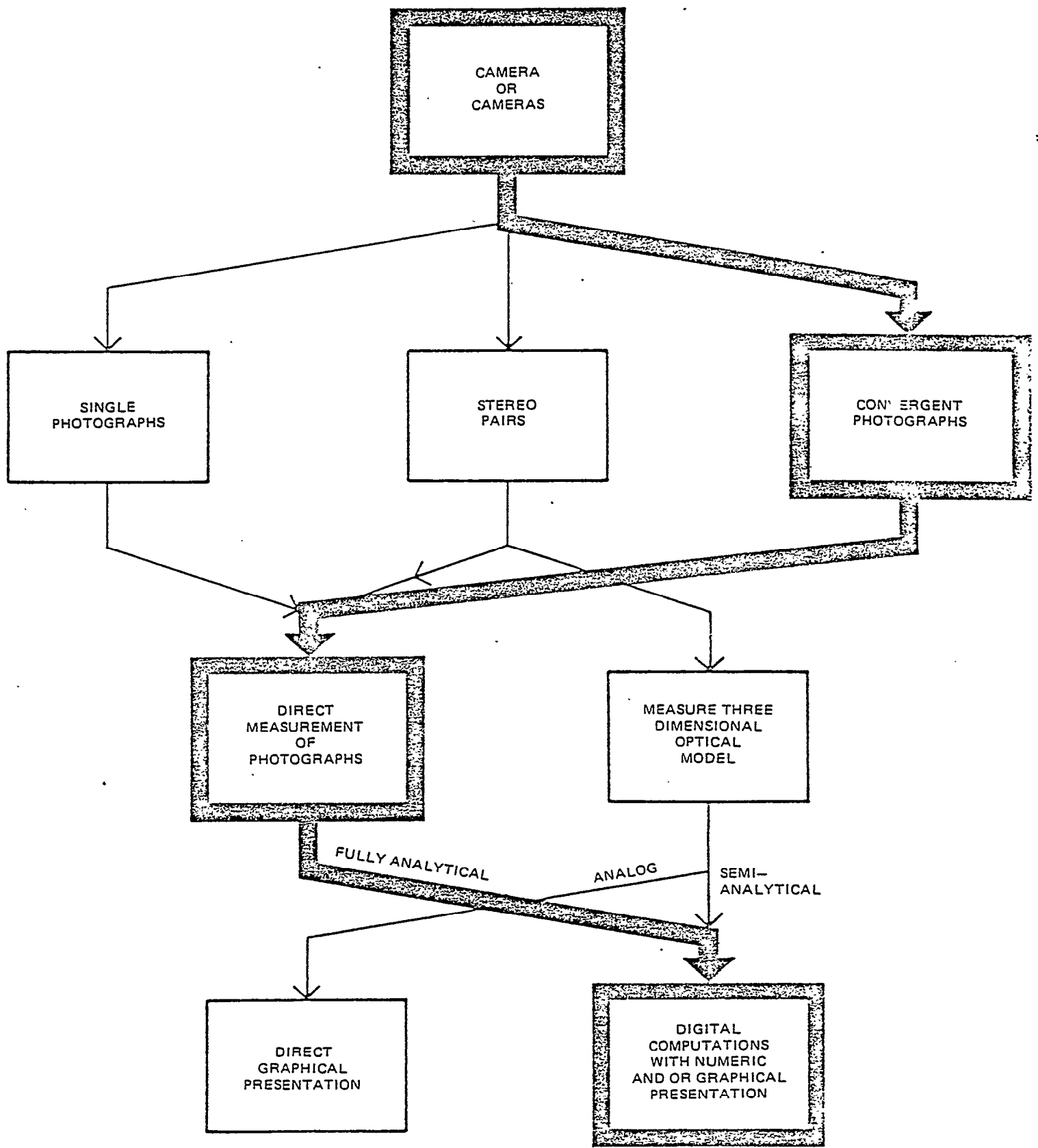


Figure 1 - Photogrammetric Solution Processes

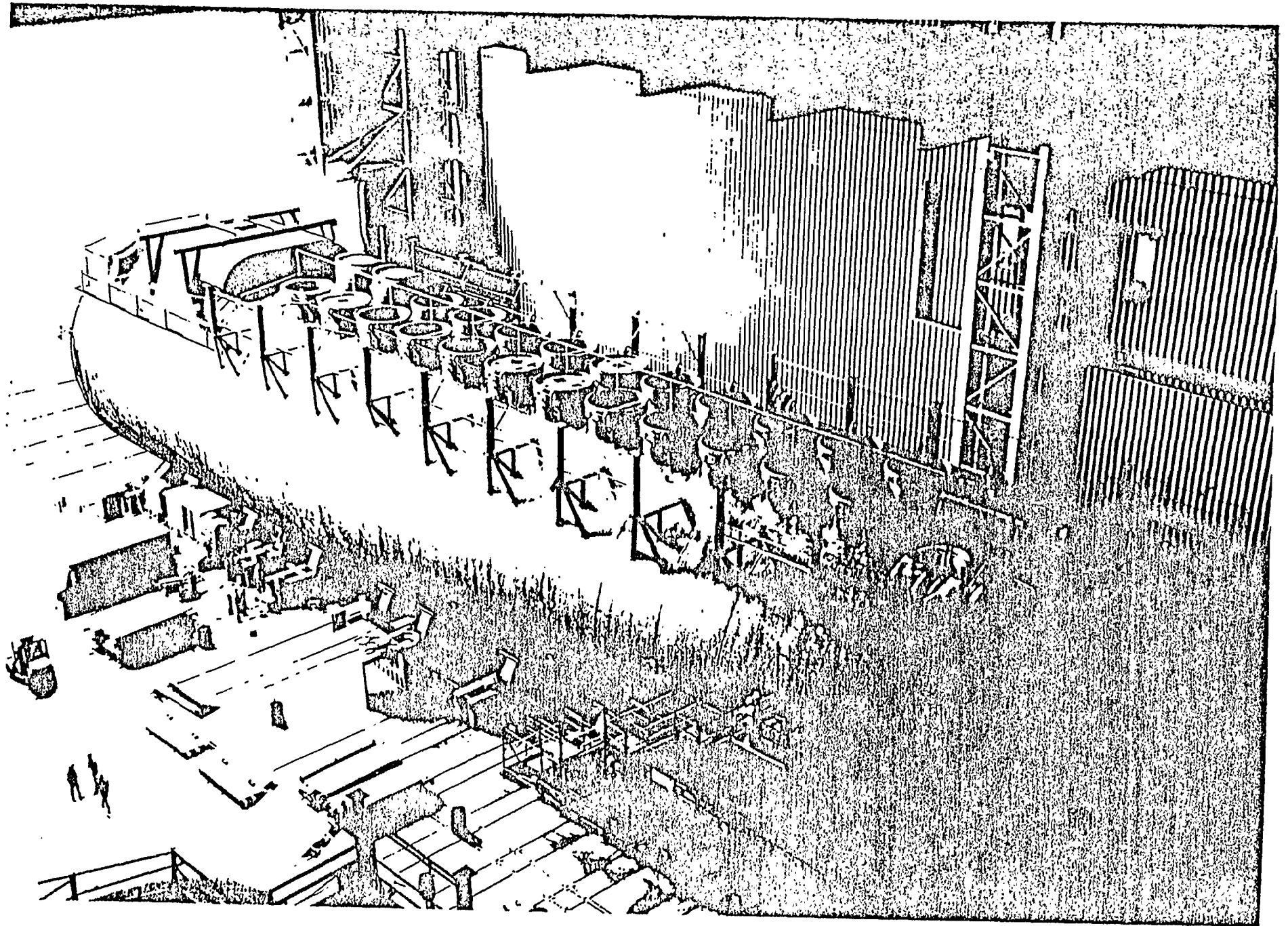


Figure 2 Typical TRIDENT Submarine Missile Compartment

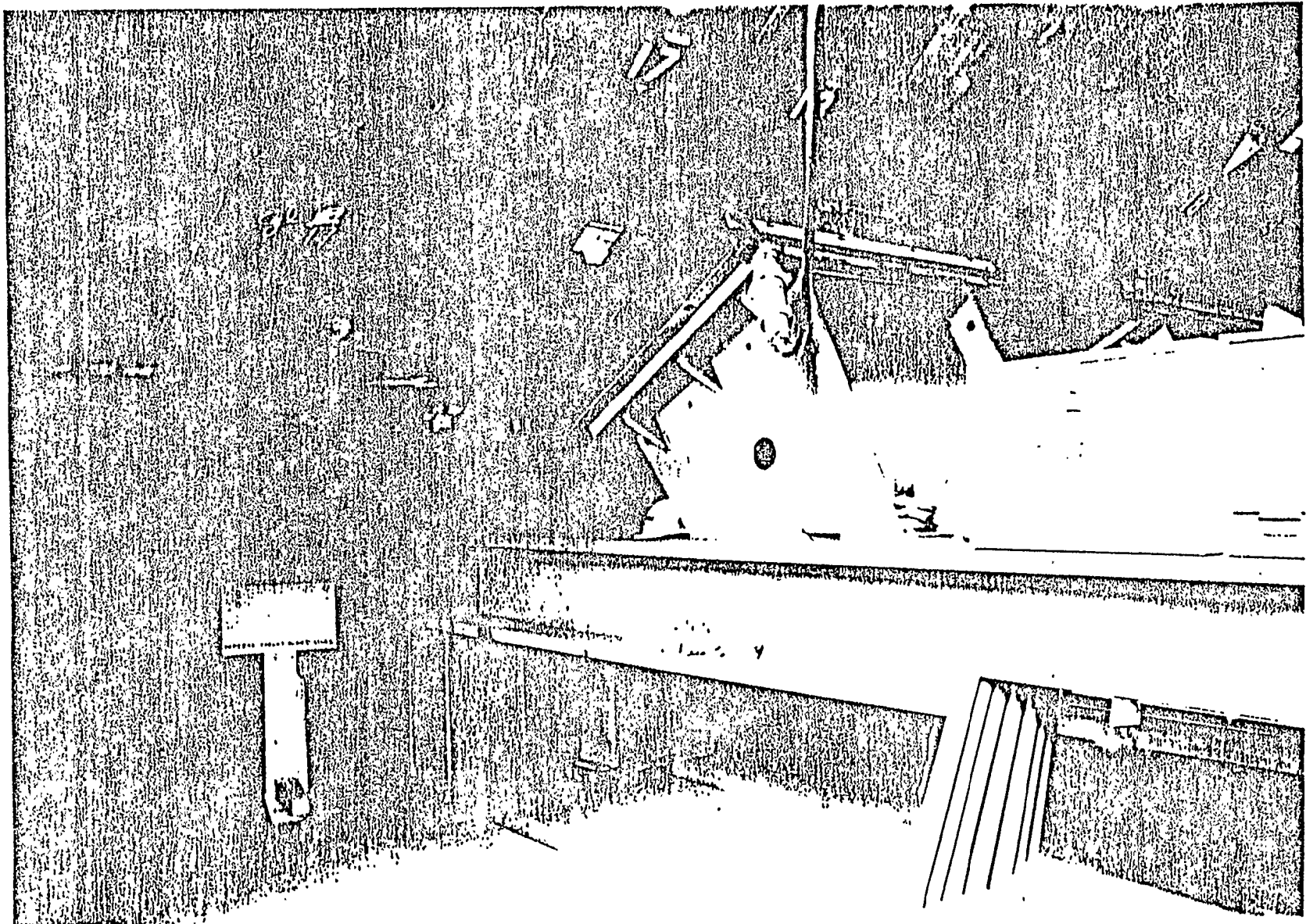


Figure 3 Strongback Arrangement Supporting
The TRIDENT Hull

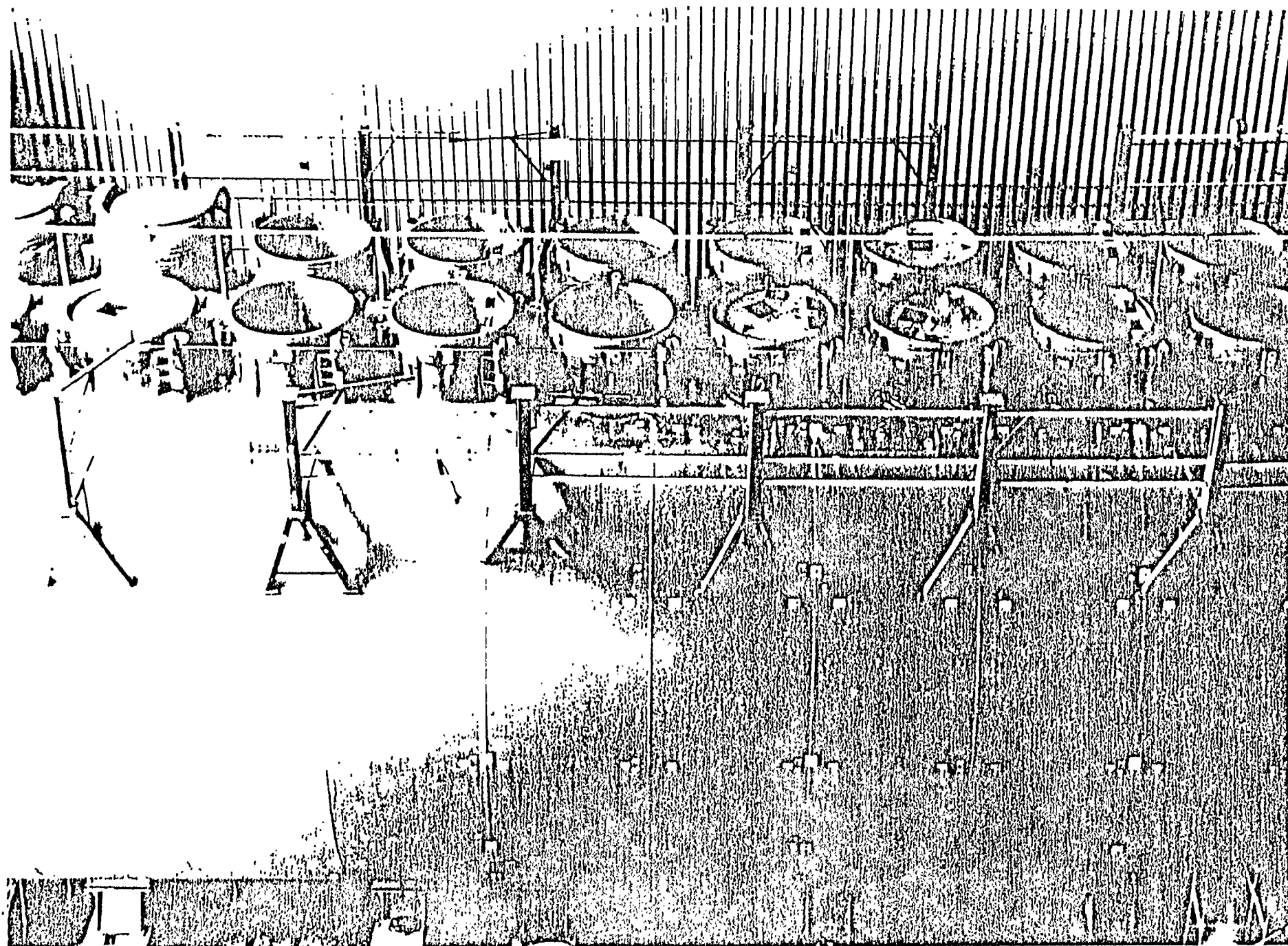


Figure 4 Blowup of Missile Tube Projections

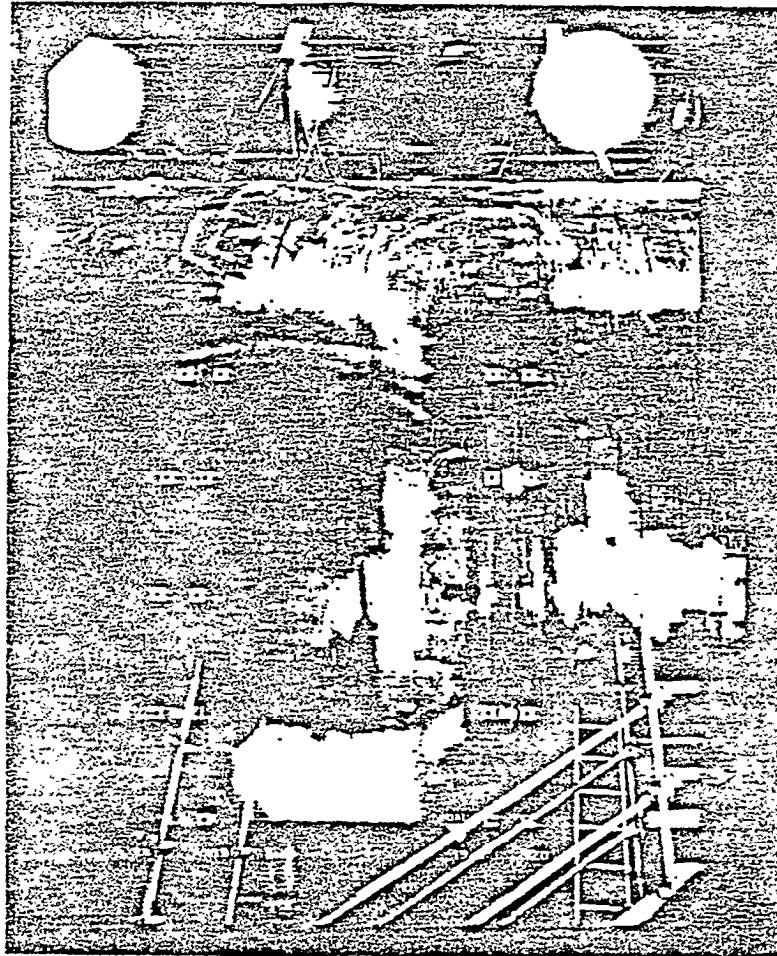


Figure 5 - Measurement Station Layout,
Showing Side of TRIDENT Hull

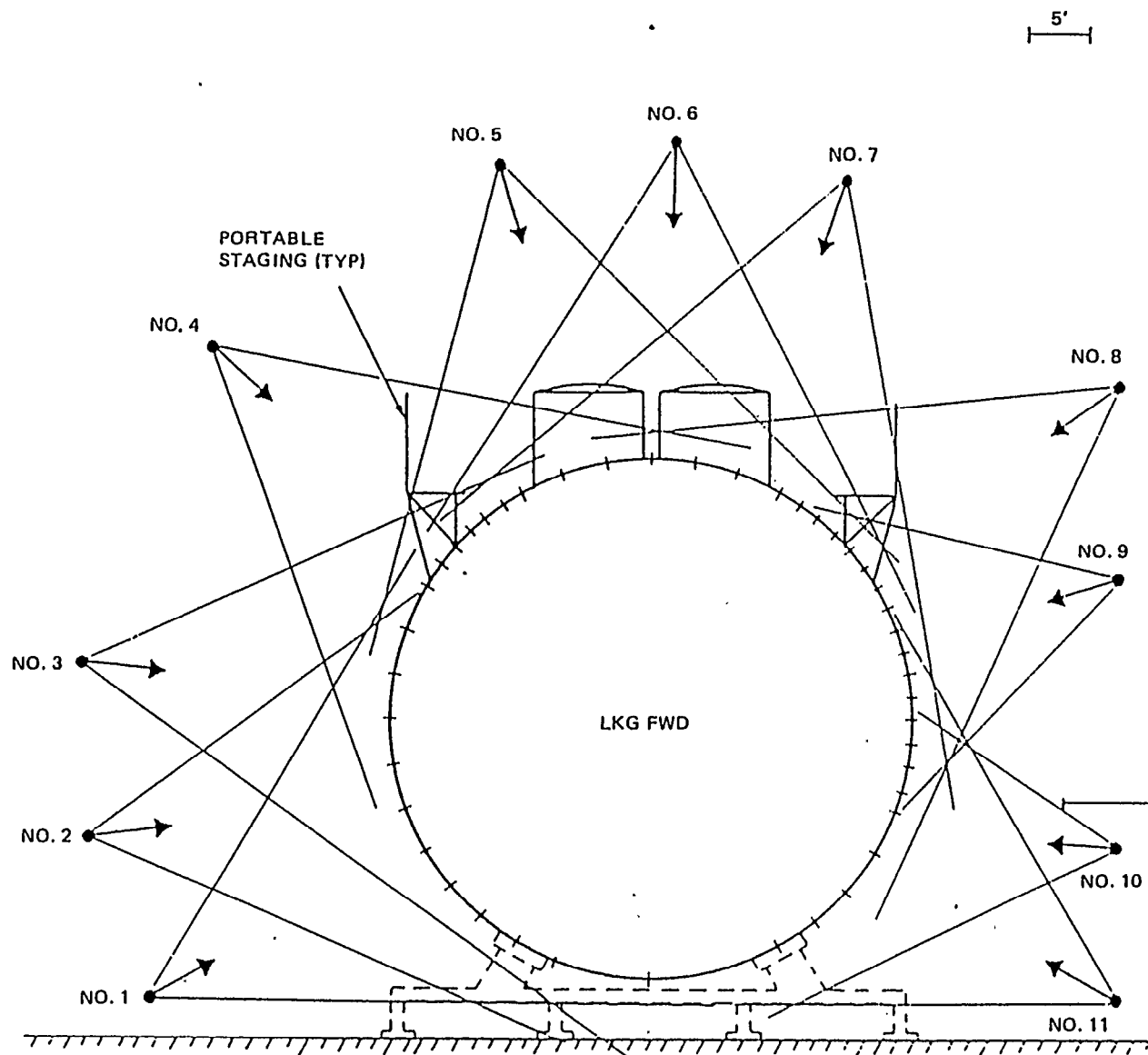


Figure 6- Photographic Plan for the Trident Hull Typical Transverse Section

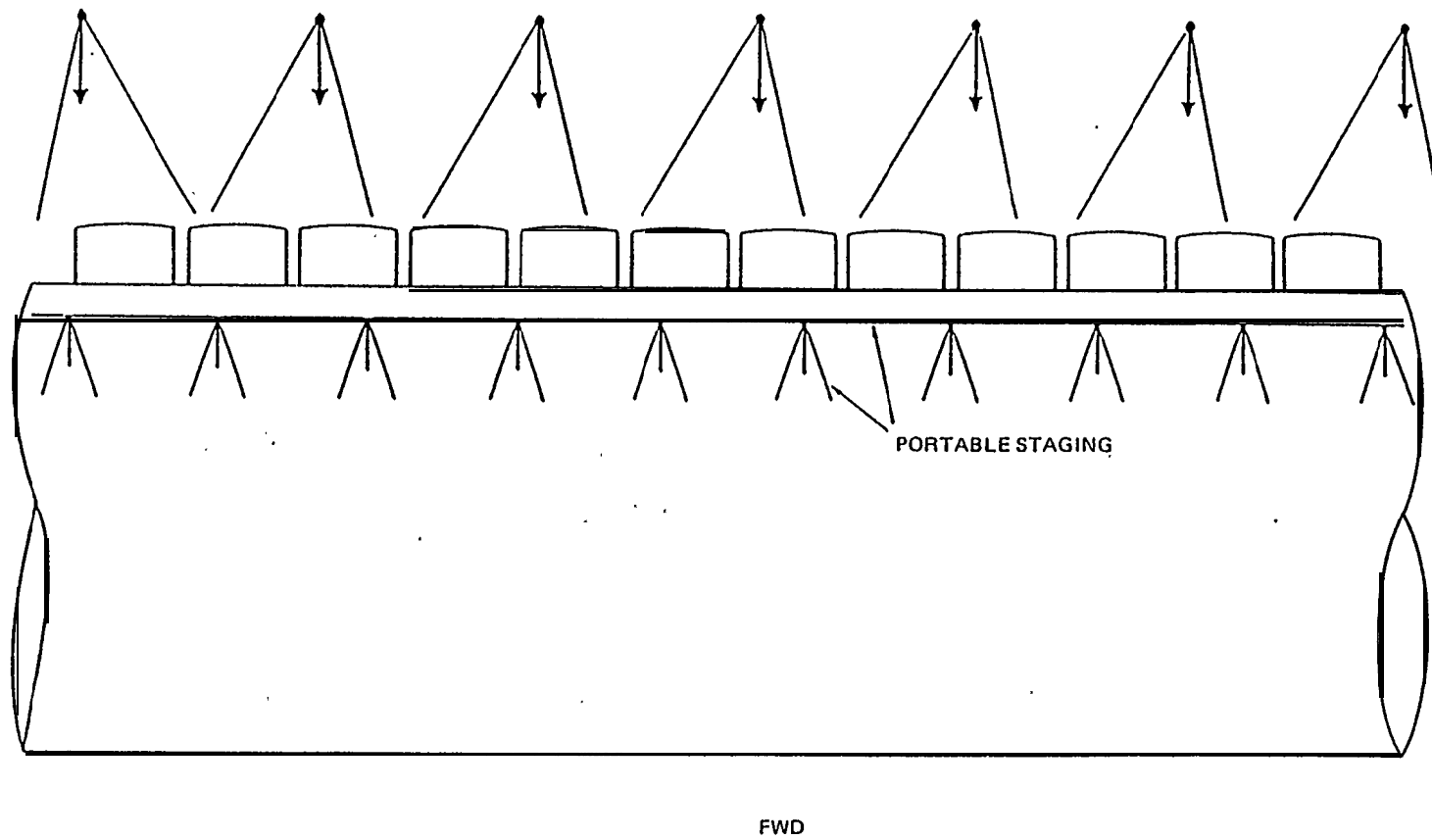


Figure 7 Longitudinal Section Showing Longitudinal Spacing of Photographs



Figure 8 Blowup Showing Photogrammetric Target
Affixed to the ERIDANI Hull

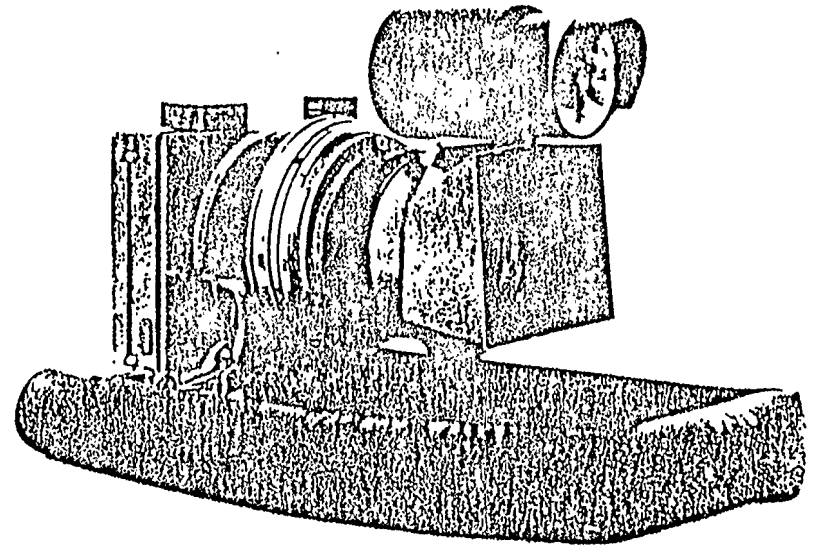
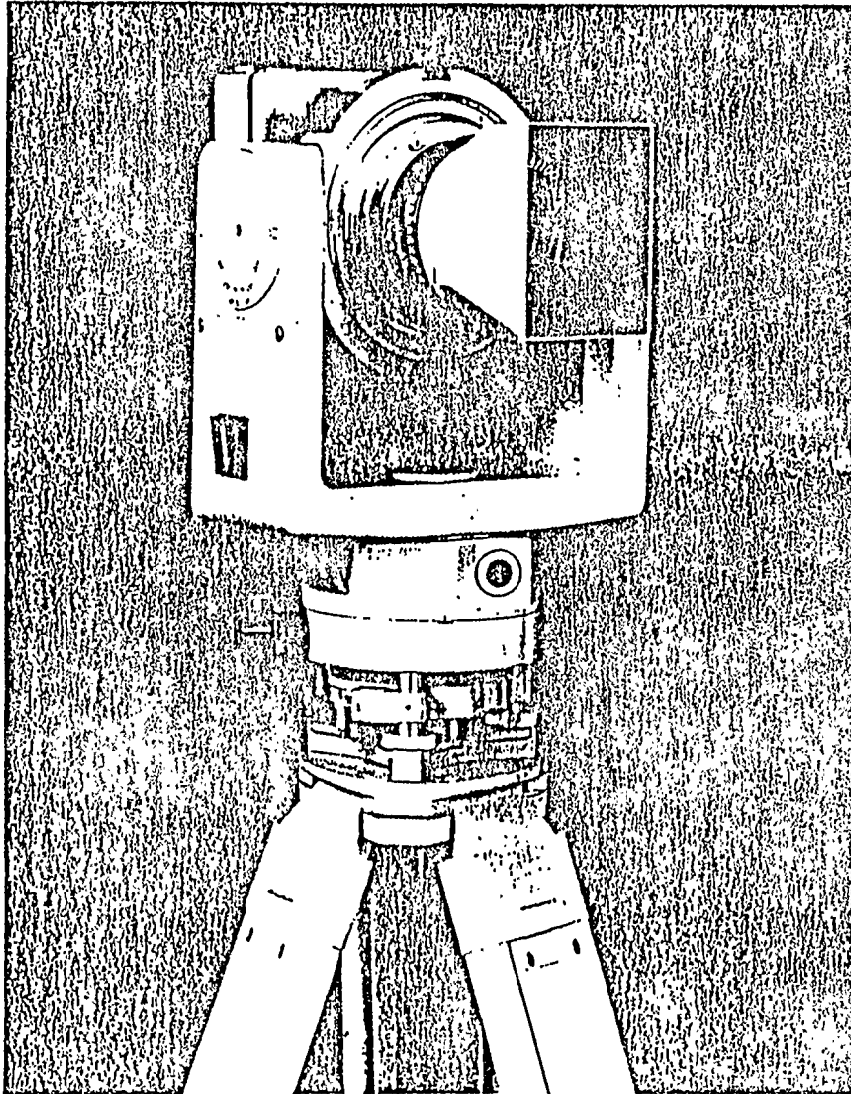


Figure 9
Wild P31 Universal Terrestrial Camera
Left: Mounted on Surveying Tripod
Above: Modified For Hand-Held Use

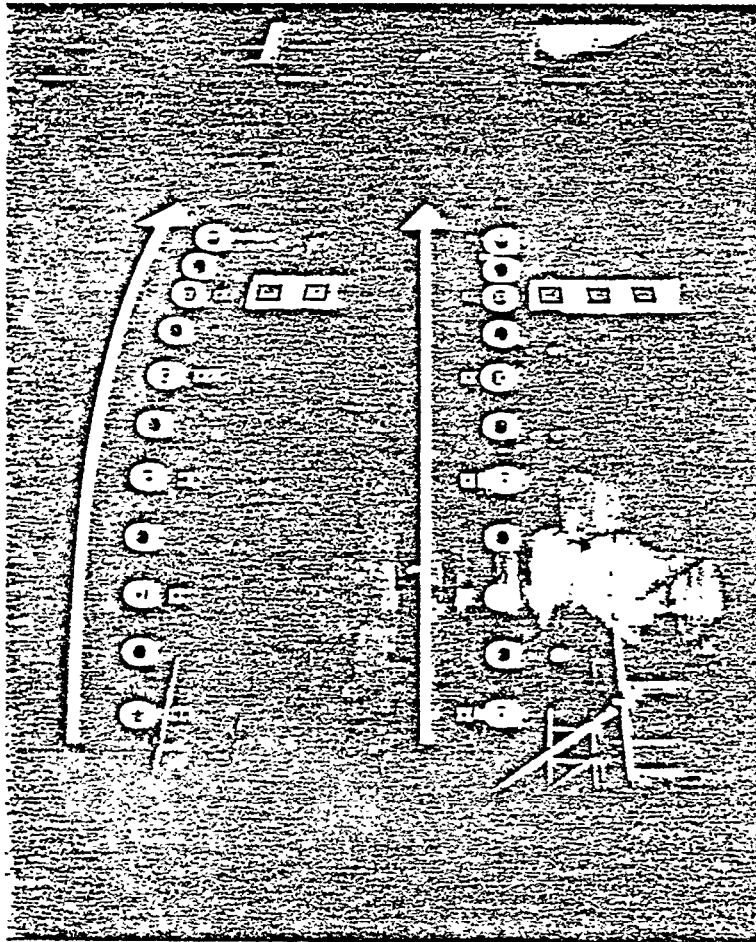


Figure 10 Typical Glass pate Negative,
Showing Measurement Layout and Targets

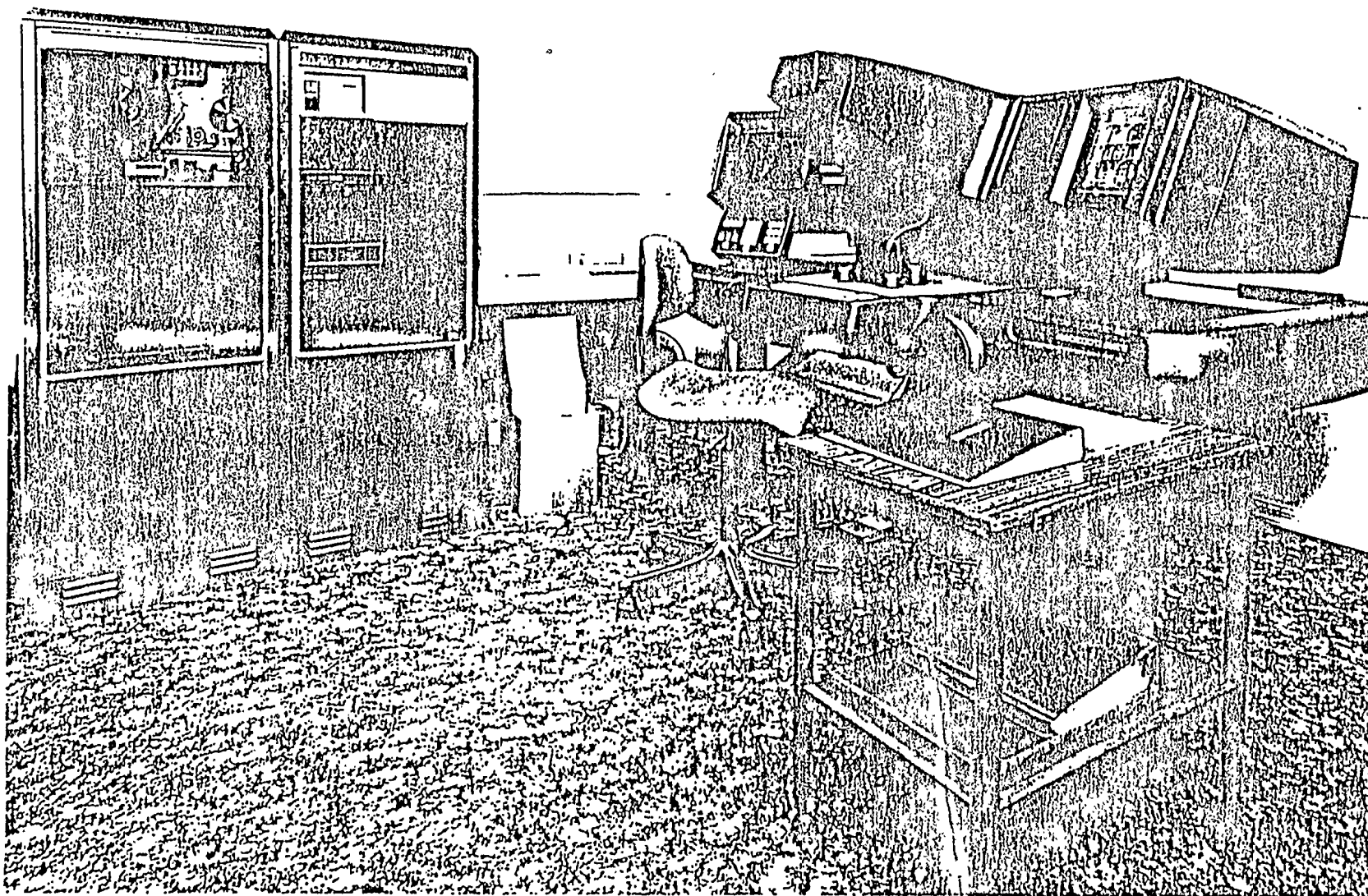


Figure 11 Wild Heerburg AC-1 Analytical Comparator
with Associated Computer System

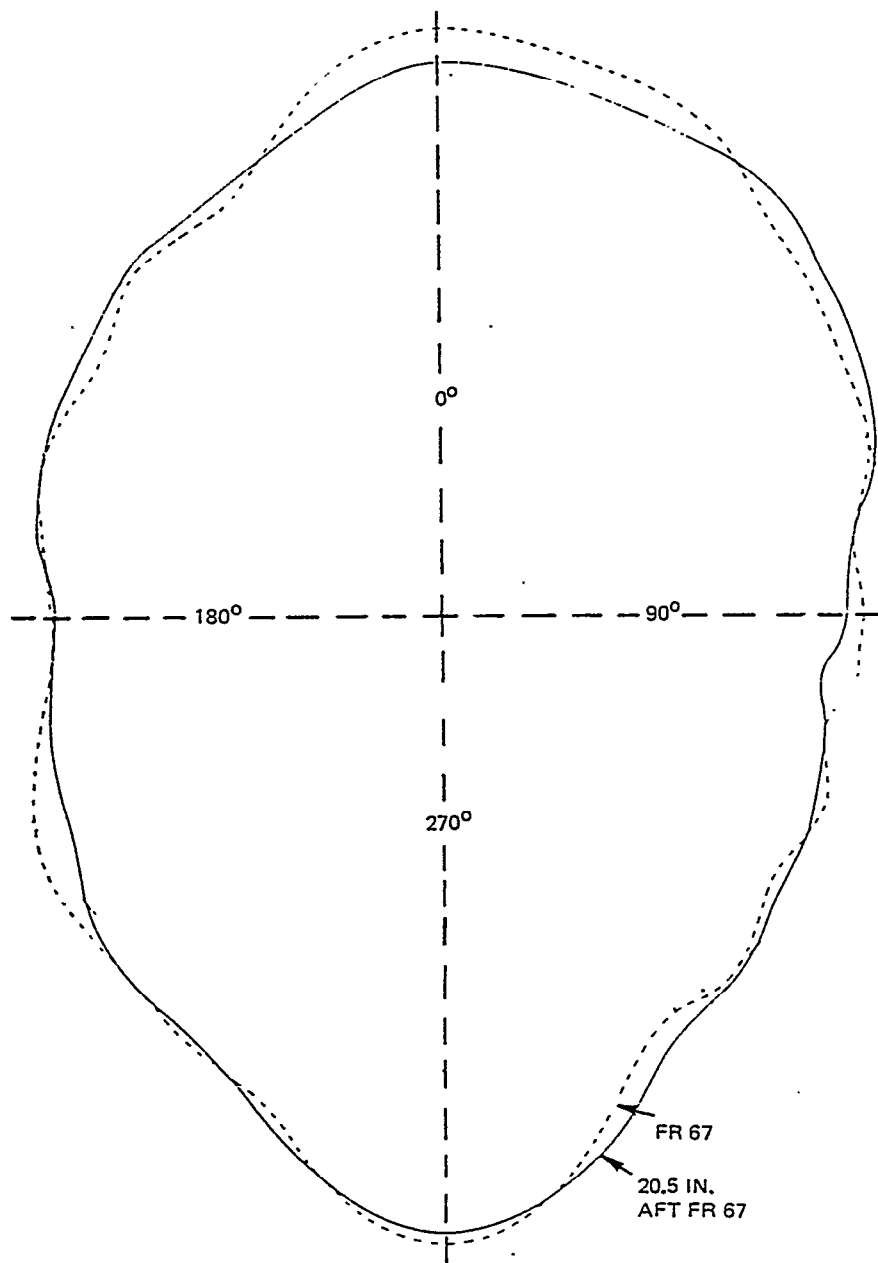


Figure 12 - Exaggerated Circularity Contour

GENERAL DYNAMICS <i>Electric Boat Division</i>		QUALITY CONTROL CIRCULARITY MEASUREMENTS <small>84-00-2908-106-79 REV 12 73</small>	
UNIT SHIP NO STATION		DATE	
<div style="display: flex; justify-content: space-between;"> <div style="width: 20%;"> LOOKING FWD/AFT. W/A # </div> <div style="width: 60%; text-align: center;"> </div> <div style="width: 20%; text-align: right;"> READINGS IN 32NDS </div> </div> <p style="text-align: center; font-size: small; margin-top: 10px;"> NOTE: PLUS (+) SIGN INDICATES ACTUAL CONTOUR IS OUTSIDE MEAN CIRCLE. MINUS (-) SIGN INDICATES ACTUAL CONTOUR IS INSIDE MEAN CIRCLE. </p>			
LINE ITEM		DRAWING NO.	
EB 509 CHITS			
CIRCULARITY BY PHOTOCGRAMMETRY			
CIRCULARITY		RADIUS	
ALLOW. DIFF.	DESIGN	MEAN	
MAX. DIFF.	ALLOW. DIFF.	ACT. DIFF.	
PLATE THICKNESS			
QUALITY CONTROL INSPECTOR	CALCULATED BY	DATE	QUALITY CONTROL FOREMAN DATE

Figure 13 - Typical EBDiv Circularity Form Documentation

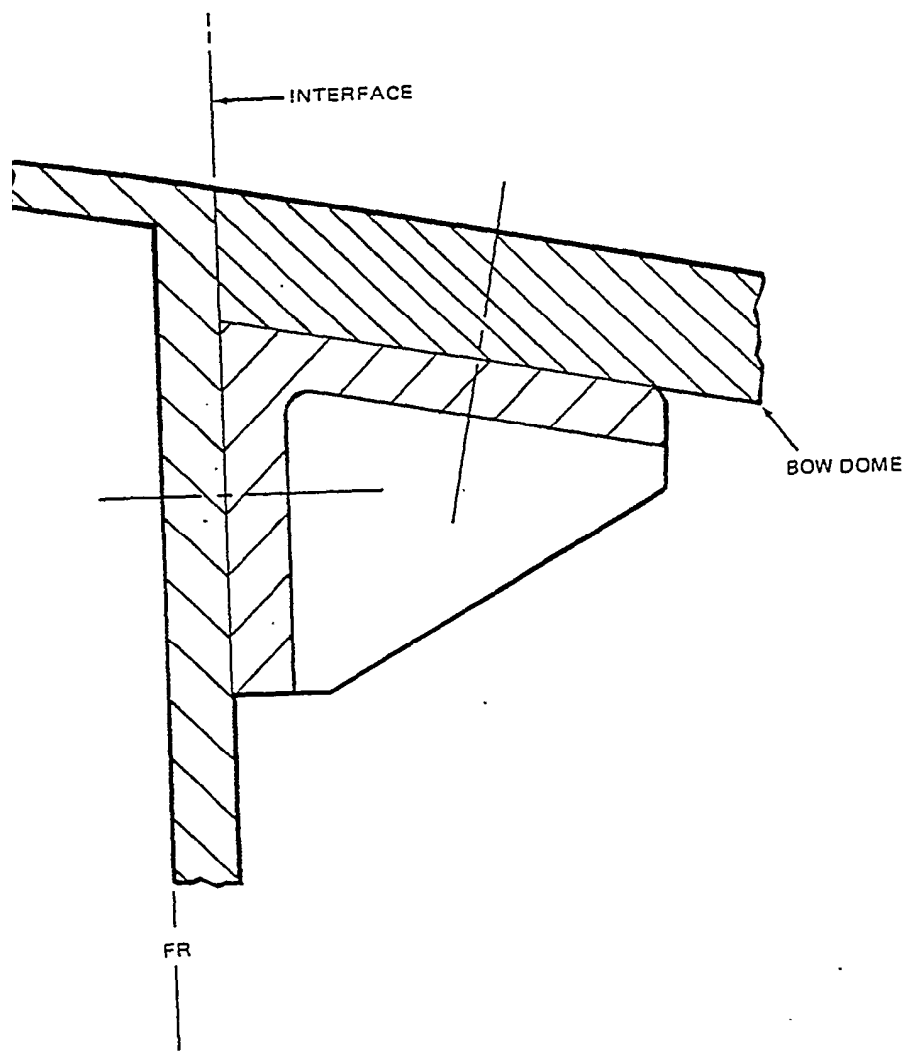


Figure 14 - Bow Dome Interface Attachment



Figure 15 - Contour Profile of
Non-Pressure Hull Interface

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